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Calibration Service for Laser Power and Energy at 248 nm

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TRADE NAME DISCLAIMER

Certain commercial components used in the calibration system are identified in this report in order to adequately document the design. Such use and identification do not imply recommendation or endorsement by NIST, nor do they imply that the items are necessarily the best available for the purpose.

CALIBRATION SERVICE FOR LASER POWER AND ENERGY AT 248 nm

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This document describes the calibration service provided by the National Institute of Standards and Technology (NIST) for laser power and energy at the excimer laser wavelength of 248 nm. The service supports the calibration of laser-power meters from 400 μW to 7.5 W, and energy meters from 80 μJ to 150 mJ per pulse. Typical expanded measurement uncertainties range from 1.6 to 2 percent. The measurement system, which includes a source laser, beam optics, and NIST reference standard calorimeters, is reviewed. Theory and design considerations for the reference calorimeters that correlate optical energy to NIST electrical standards are discussed. Critical components of the calorimeters and beam delivery system are specified. Measurement-system parameters and calibration procedures are examined. Types of laser meters suitable for calibration are delineated. A detailed analysis of sources of error, estimates of uncertainty, and expanded uncertainty are presented.

KEY WORDS: beamsplitter; calorimeter; excimer laser; laser power; pulse energy

1. INTRODUCTION

The rapid growth in the commercial application of excimer lasers has resulted in a compelling need for corresponding NIST standards and measurement services. Excimer lasers are now being used in semiconductor photolithography, medical procedures, and a variety of materials-processing applications.

Electromagnetic radiation from excimer lasers has several characteristics which make accurate power or energy measurements difficult. A device to be used for measuring excimer laser power or energy must accommodate electromagnetic energy having spatial and temporal coherence, high irradiance, nonuniform intensity profiles, and photon energies high enough to cause fluorescence or exceed strengths of chemical bonds.

NIST measurement of laser energy at the excimer wavelength of 248 nm is accomplished using a pulsed-laser calorimeter. Reference standard calorimeters (QUV-1 and QUV-2) were designed and constructed at NIST to measure the total energy injected during a prescribed period of time [1][2]. Laser pulses are received by a cavity designed to absorb the energy and produce a corresponding temperature change. The calorimeters are electrically calibrated and traceable to national-standard electrical quantities.

A measurement system consisting of a reference standard calorimeter, source laser, beamsplitter and collimation optics, and computer-controlled data acquisition instrumentation is used to calibrate laser power or energy meters. Two calorimeters were built both to allow evaluation of the beamsplitter properties and for redundancy.

2. DESIGN PHILOSOPHY AND CONSIDERATIONS FOR THE 248 nm CALIBRATION SYSTEM

Previous NIST research in laser calorimetry yielded the development of instruments capable of measuring absolute total energy of pulsed radiation from Nd:YAG lasers operating at 1064 nm [2]. This Q-series design was selected for the excimer laser calorimeter due to its ability to absorb short pulses of laser radiation without suffering damage. The design was adapted for pulsed 248 nm excimer lasers by using a suitable absorbing material. The 248 nm version, or QUV calorimeter, is the resulting device and serves as the reference standard for the calibration system. Physical dimensions and principles of operation of the QUV calorimeters for excimer laser energy are essentially the same as for the Q-series model. As a result, the uncertainty assessment and expanded uncertainty estimates are similar. High absolute accuracy and precision are the primary goals of the 248 nm calibration system.

2.1 Advantages of the QUV Calorimeter Reference Standard

The design of the QUV calorimeters is based on the theory of isoperibol calorimetry [3], in which the temperature of the energy absorber changes while the temperature of the surroundings remains constant. The principal objective is to absorb all the incident laser radiation and convert the optical energy to thermal energy. Isoperibol calorimetery has been thoroughly investigated for many years and provides a mechanism for correlating optical energy to electrical energy. Energy measurements by the QUV calorimeters are traceable to fundamental NIST standards by electrical-substitution calibration. The expanded uncertainty for a QUV standard calorimeter is on the order of 0.8 percent, which is consistent with other NIST laser standards.

The ability to withstand very high peak power laser pulses is also an essential benefit of the QUV calorimeter design. Two calorimeters are needed for measurement of the beamsplitter ratios and to simplify the system configurations necessary for practical calibrations.

2.2 Limitations of the QUV Calorimeter Calibration System

While the QUV calorimeter design provides a robust reference standard for 248 nm laser energy, the limited range of input energy (0.6 to 15 J) of linear operation requires beam attenuation to extend the useful measurement limits of a calibration system. Disadvantages of beamsplitter attenuation techniques include an increase in the overall uncertainty of a measurement and a more complex optical alignment.

Because of their design, the calorimeters are relatively slow, and are not easily portable or simple to use. Consequently, the QUV measurement system is not used to calibrate laser sources directly but primarily to calibrate more conveniently operated meters for laser power or energy.

Good beam collimation is also required for light to propagate through the QUV calorimeter aperture tube and to allow total absorption of the laser pulse energy. Collimation of the laser beam requires extra lenses and alignment procedures. Measurement uncertainty is increased due to the destructive effect of ultraviolet light on beam optics and absorber surfaces. Consequently, more frequent

quality-control procedures such as measurements with laser beamsplitters are used to monitor any changes in the ratio.

Lower uncertainties are possible if improvements in laser pulse stability and beamsplitter optics can be achieved. In the present design form, the estimated practical limit of uncertainty in the QUV calibration system is about 1 to 1.6 percent.

3. DESCRIPTION OF THE 248 nm CALIBRATION SYSTEM

A simplified diagram of the calibration system is shown in Figure 1. The principal subsystems of the calibration system are:

A. Excimer laser: source of 248 nm radiation

B. Beam-steering and collimating optics

C. Multiple-reflection beamsplitter/attenuator

D. Data-acquisition and processing electronics

E. QUV reference-standard calorimeter

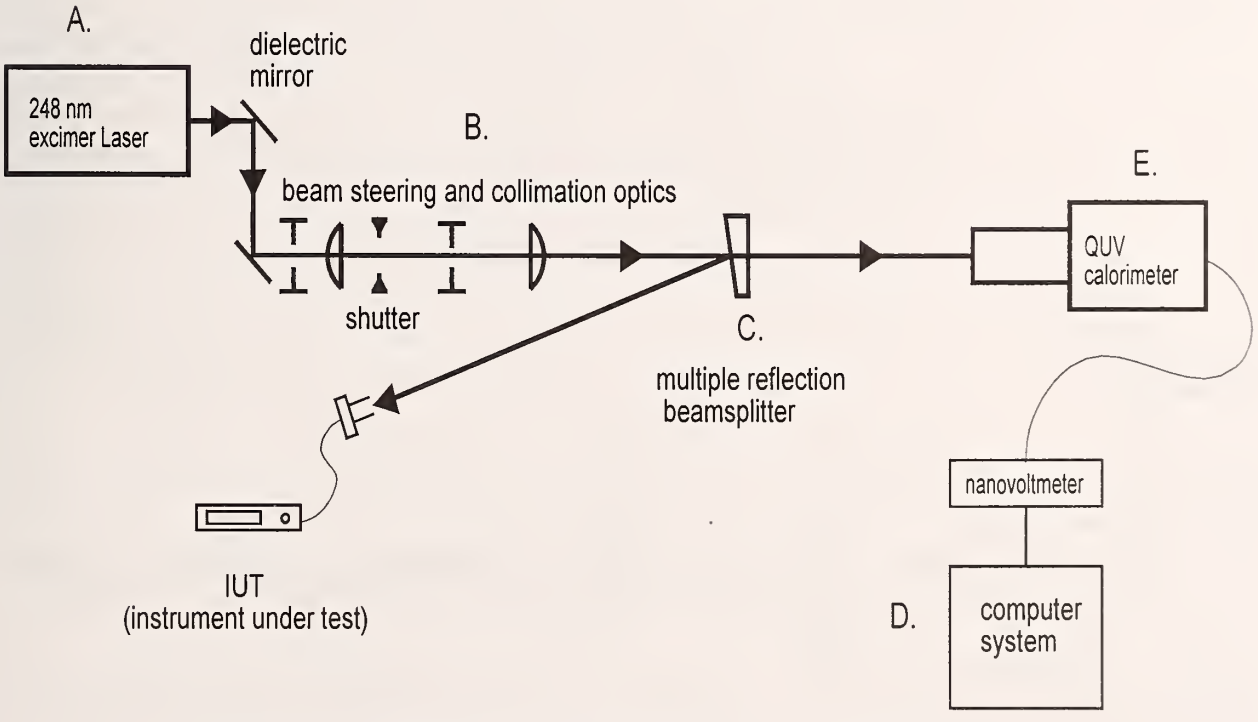

Figure 1. System for calibrating laser power and energy at 248 nm.

All the instruments shown in the diagram except the excimer laser and the computer system are maintained in an acrylic resin enclosure. This enclosure maintains a thermal buffer from the rest of the room, shielding the calorimeters from drafts and rapid variations in temperature of the building heating/cooling system. Acrylic resin is opaque to ultraviolet wavelengths, which prevents reflected or scattered 248 nm light from leaving the measurement table.

3.1 Excimer Laser Source

The source of ultraviolet radiation is an excimer laser using KrF gas as the lasing medium and operating at a wavelength of 248.4 ± 0.7 nm. The peak rated output energy of the laser is about 400 mJ/pulse. However, beam-steering mirror and lens losses, aperturing, and pulse stability constraints reduce this to 150 mJ maximum pulse energy. Pulse duration is approximately 30 to 35 ns, full width at half maximum (FWHM). This laser provides pulse rates of 0.1 to 50 pulses/s, but has been modified to provide up to 100 pulses/s under very restricted conditions.

The intensity profile of the output beam is rectangular with approximate dimensions of 10 mm × 30 mm at a distance of 1 meter from the laser. The profile is nonuniform, with intensity variations occurring with a quasi-interference pattern. This pattern is evident regardless of input aperture size. Corrosive etching of the antireflection coating from the laser output mirror by the ultraviolet radiation is the likely cause of the interference pattern. The output beam is unpolarized and has a spectral width of about 0.3 nm.

3.2 Beam Steering and Collimating Optics

The raw laser beam has relatively high angular divergence (> 3 mrad, full angle) and must be collimated to function with the long beam paths required by the beamsplitter system and the aperture tube of the QUV calorimeter. Different values of beam divergence in the horizontal and vertical dimensions complicate this task, so the final degree of collimation is a compromise sufficient to operate within the constraints of the physical layout. Figure 2 shows the detail of the beam steering mirrors and collimating lenses.

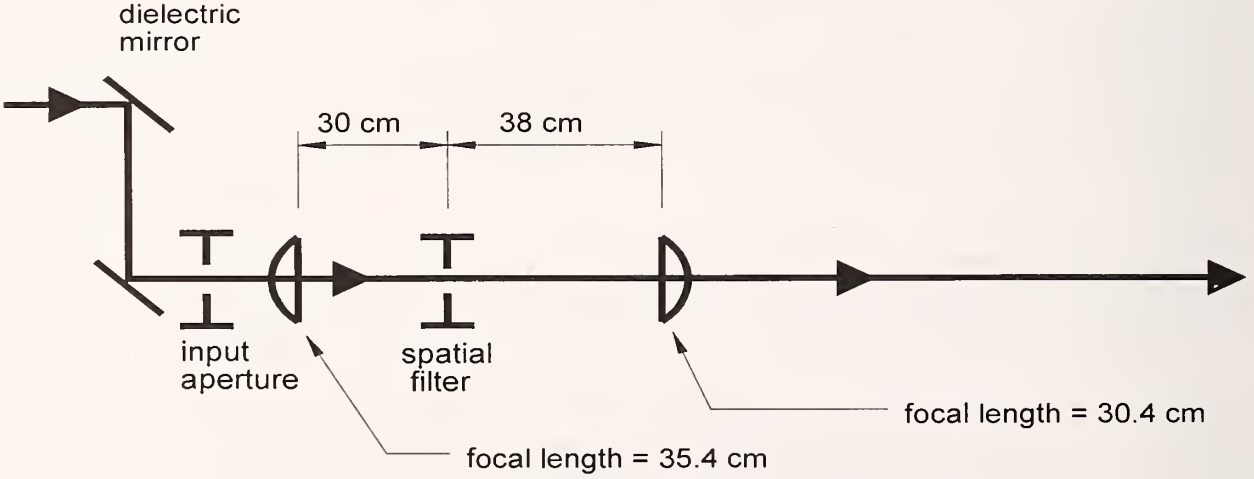

Figure 2. Details of beam steering and collimation optics.

The input and spatial-filtering apertures are circular irises which can be adjusted to collimate and provide varying beam sizes. The resulting beam irradiance appears circular, but the major portion of the energy is still contained in a rectangular area within the profile. Lenses and apertures are mounted on an optical rail and allow fine tuning of the collimation, with the ability to expand the beam slightly to reduce energy density.

Spatial filtering is implemented with a variable aperture near the common focal points of the lenses, providing improved collimation. The method is simple but does not appreciably homogenize the beam, so the interference pattern remains. Adjustments to the laser cavity mirrors to remove the interference pattern result in a drastic drop in output energy. Beam-profile equipment necessary to measure the degree of nonuniformity in the intensity pattern is not presently available to us, so the exact spatial distribution is unknown. However, the calorimeter response and beamsplitter ratios are relatively insensitive to the estimated levels of nonuniformity in the laser beam.

3.3 Multiple Reflection Beamsplitter Attenuator

NIST makes extensive use of multiple-reflection, wedged beamsplitters for attenuation in calibration systems for laser power or energy. The theory and use of wedged beamsplitters have been well documented [4][5]. A brief summary of beamsplitter application for the QUV system follows.

There are two principal advantages to using beamsplitters in laser measurements. If the two detectors used with the beamsplitter both measure total energy, then laser stability is not important since the detectors are monitoring the beam at the same time. Power measurements require a stable laser, but it is a less critical issue when using the beamsplitter method than a substitution method. Another important advantage is that the beamsplitter extends the range of the reference calorimeter since the beamsplitter can function as a calibrated attenuator.

A multiple-reflection beamsplitter (Figure 3) is a wedged, transparent optical component that has highly polished flat surfaces and is made of a well characterized material. The relative powers of the emerging beams can be calculated by applying both Snell's and Fresnel's laws of reflection and refraction for dielectric materials. This requires knowledge of the index of refractive, the wedge angle, the angle of incidence, and the polarization of the incident laser beam. In the ultraviolet wavelength region, fused silica is one of the few materials that can be used for this purpose. It has been thoroughly studied at various wavelengths, and its dispersion equation is well documented [6].

There are different techniques to align the beamsplitter in the laser beam and produce a consistent angle of incidence. The beamsplitter can be oriented so that the incident beam bisects the reflected $m = -1$ and $+1$ beams. This orientation provides a small incident angle, but requires long path lengths to get the necessary physical separation of the different beams. This method is less susceptible to polarization effects than methods with a large angle of incidence.

An alternate method provides the required beam separation by increasing the angle of incidence. In this method, the transmitted $m = +2$ beam is retroreflected back on itself and through a small hole in a card. The beamsplitter is then rotated until the $m = +2$ retroreflection is concentric with the $m = +3$ beam. When this condition is achieved with a 248.4 nm wavelength laser beam, then the angle of incidence is approximately 9.07°.

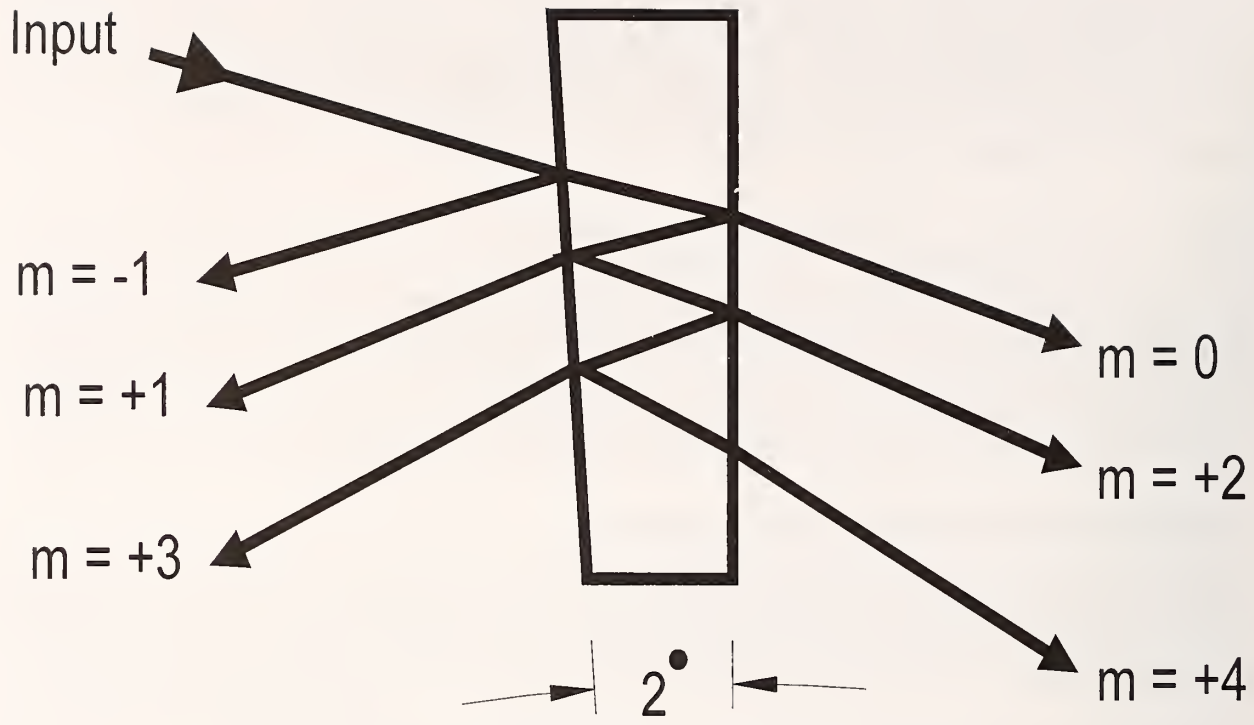

Figure 3. Multiple reflection wedged beamsplitter.

Material: SiO_2 , UV grade fused-silica
Wedge Angle: 2.0 ± 0.1°
Wavelength: 248.4 ± 0.7 nm
Index of Refraction: 1.5083 ± 0.0004
Angle of Incidence: −9.07 ± 0.04°
Index of Refraction of Air: 1.00024 ± 0.00001

Attenuation factors for the ratio of useful "m" orders of the beamsplitter have been calculated for fused silica at the wavelength of 248.4 nm and an incident angle of 9.07° are shown in Table 3.1. These values are calculated for comparison to experimental measurements of the beamsplitter ratio using a 248.4 nm laser and the QUV calorimeters. The calculated, theoretical ratios are used as guidelines at this wavelength.

Table 3.1. Theoretical beamsplitter ratios.

Beam A (order, m=)	Beam B (order, m=)	Ratio A/B vertical polarization	Ratio A/B horizontal polarization	Ratio A/B mixed polarization	% difference of V & H polarization
0	+1	24.01 ± 0.12	24.75 ± 0.12	24.38 ± 0.12	3.05
+1	+2	24.28 ± 0.12	24.47 ± 0.12	24.38 ± 0.12	0.77
0	+2	583 ± 3	606 ± 3	594 ± 3	3.82

The ratio of the power or energy in the transmitted beam to that in the reflected beam can be confirmed for a particular beamsplitter at a specific laser wavelength by using the standard calorimeters or two linear detectors to simultaneously measure two beams. A set of ratio measurements is made, then the two detectors are interchanged, and the measurements are repeated. Then the square root of the product of the two ratio averages is calculated. Ideally this method cancels the uncertainty of the calibrations of the two detectors from the measurement [7]. It is particularly important to measure the beamsplitter ratios periodically because even high purity UV-grade fused silica suffers damage, resulting in a modification of optical properties, under high fluence 248 nm irradiation [8].

Beamsplitter ratios were measured on a fused-silica wedge at 248.4 nm; the results are shown in Table 3.2. The measured values differ from theoretical ratios by almost 4 percent for the 0/+1 ratio and about 1 percent for the +1/+2 ratio. Initial measurements gave a 0/+1 ratio within 2 percent of the theoretical value. Measured values have shown a tendency to differ by 1-4 percent from the theoretical value over the three-year period the QUV system has been in testing or operation, possibly due to UV damage. However, the direction in which the ratio differs is not always the same. As a result, the measured ratios are considered to be more appropriate than theoretical values, and the ratio obtained from current beamsplitter data is used to calibrate laser power or energy meters.

Corroborating evidence for modification of the spitter ratio by UV exposure comes from ratio measurements made on a second fused-silica beamsplitter (#2) which was purchased at the same time and from the same manufacturer as the operational beamsplitter (#1). This splitter is kept in storage as a reference. Preliminary measurements of laser beamsplitter ratios have been made on this component, and the ratios are within 1 percent of the theoretical values.

Avoiding surface damage to the fused-silica beamsplitter from high-energy UV photons requires that surfaces be kept especially clean. Long-term effects from UV irradiation may change the index of refraction, or produce damage centers. As a consequence, beamsplitter measurements are performed either before or after every calibration procedure to monitor any change in the ratio. This detects any shift in the beamsplitter ratios, which have been gradually changing with exposure.

The ratio 0/+2 is calculated from the measured ratios. The energy range of the calorimeters does not allow direct measurement of ratios over 26 to 1.

Table 3.2. Measured beamsplitter ratios.

Beam A (order, m=)	Beam B (order, m=)	Ratio A/B mixed polarization
0	+1	25.3 ± 0.3
+1	+2	24.5 ± 0.3
0	+2	620 ± 11

3.4 Data Acquisition and Processing Electronics

QUV calibration system control and data analysis are achieved with a computer using the IEEE-488 bus architecture. The interconnection schematic of the data-acquisition system is shown in Figure 4. A high-resolution nanovoltmeter measures the voltage of each QUV calorimeter thermopile. Measurement of the voltage drop across the standard resistor and heater resistor during electrical calibrations is performed with a separate digital voltmeter.

Calorimeter Nanovoltmeter: This nanovoltmeter is a 6½ digit instrument capable of 1 nV resolution on its most sensitive range (3 mV). This instrument is used to measure all dc voltages generated by a QUV calorimeter thermopile during a laser or electrical calibration. Each calorimeter is connected to an individual nanovoltmeter for this purpose. These instruments are calibrated annually by the manufacturer and are traceable to NIST voltage standards.

Electrical Calibration Digital Voltmeter (DVM): The voltage and current values being used to electrically calibrate the QUV calorimeters is measured with a digital voltmeter. This instrument is a 6½ digit device and therefore has a resolution of 1 μV on the 1 V range. Current through the electrical calibration resistance heater is determined by measuring the voltage drop across the standard resistor (see Figure 8). This DVM can also be used to measure the voltage output of the IUT if it provides an analog output port. This device is calibrated annually by the manufacturer, and traceable to NIST voltage standards.

Electrical Calibration Programmable Power Supply: Electrical calibrations are performed on the QUV calorimeters by supplying power to the resistance heater with a programmable power supply. The voltage usually applied to the heater is on the order of 1 to 6 V dc, at 10 to 70 mA of current. The calorimeter heater resistance is 133.25 ± 0.03 Ω. The output of this power supply is measured with the annually calibrated digital voltmeter (DVM).

Standard Resistor: Electrical calibration of the QUV calorimeters depends on current values calculated from the measured voltage drop across the standard resistor. The standard resistor has been calibrated by the NIST Electricity Division, and is checked annually with a resistance meter. The meter which measures resistance is calibrated annually by the manufacturer and is traceable to NIST standards.

Injection Shutter System: The laser energy used in a measurement is controlled by a mechanical shutter system consisting of the shutter and a driver unit. The computer controls the shutter, which switches on the order of a few milliseconds. The shutter has two blades, which can operate to completely block or pass the laser radiation. This unit operates fast enough to allow a predetermined number of pulses to pass at our typical excimer laser pulse-repetition rates.

Switch/Control Unit: A switching and control unit is used to sequentially supply measurements from the various electronic equipment to the controlling computer. This unit can also be used to route an analog signal from a customer's meter to the digital voltmeter to record voltage readings during a calibration.

Computer Controller: A computer controls the tests and the data-acquisition equipment. This computer performs such operations as turning on and off the pulsing of the laser, opening and closing the shutter, acquiring voltage data, processing the data, and displaying the results. All communication to and from the instruments is carried out over the IEEE-488 bus, except for serial communication with the excimer laser and the injection shutter. Commercial instrument-control software is used along with a custom written program to acquire and analyze the data. The acquisition-and-analysis program was written by an outside contractor with NIST collaboration and then tested in the QUV laboratory.

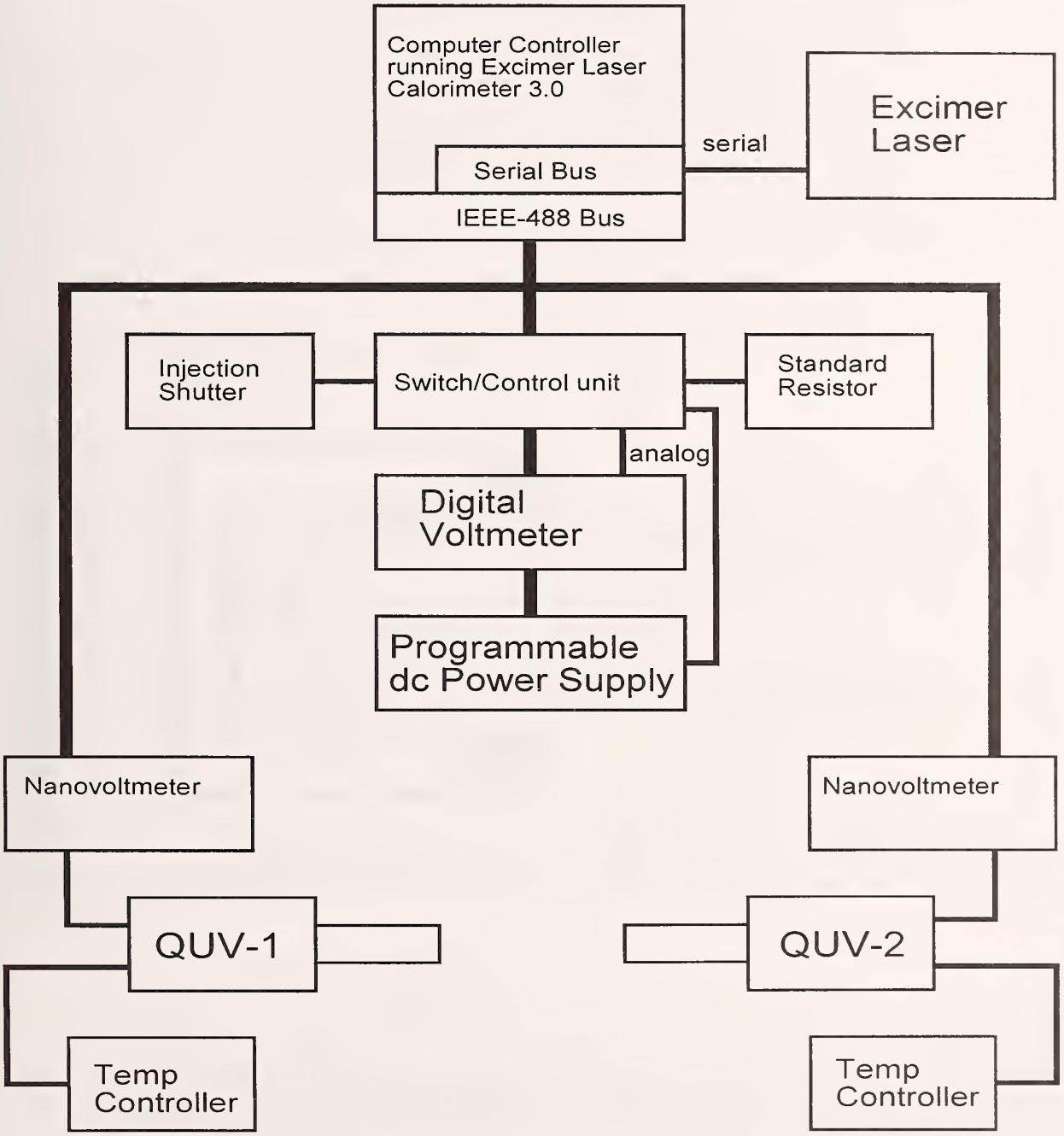

Figure 4. QUV calibration system schematic.

4. QUV STANDARD CALORIMETERS

The principal objective of the QUV laser calorimeter is to absorb all the incident laser radiation and convert the electromagnetic energy to thermal energy. The resulting temperature change is then used to determine the amount of absorbed optical energy. Each excimer laser calorimeter (Figure 5) consists of an absorbing cavity suspended inside a temperature-controlled jacket which provides a constant (with respect to time) temperature environment. This design is called an isoperibol calorimeter.

The absorbing cavity is made of thin-walled copper whose outside surface has been gold plated. Laser energy is predominantly absorbed by volume absorbing glass placed at the back of the cavity structure. · The inside surface of the cavity is coated with a flat black paint to absorb any light reflected or scattered from the glass. Because of their design, these instruments are essentially energy-storage devices; consequently the calorimeter cavity continues to rise in temperature as energy is injected. It is this temperature change that is measured and correlated to energy absorbed.

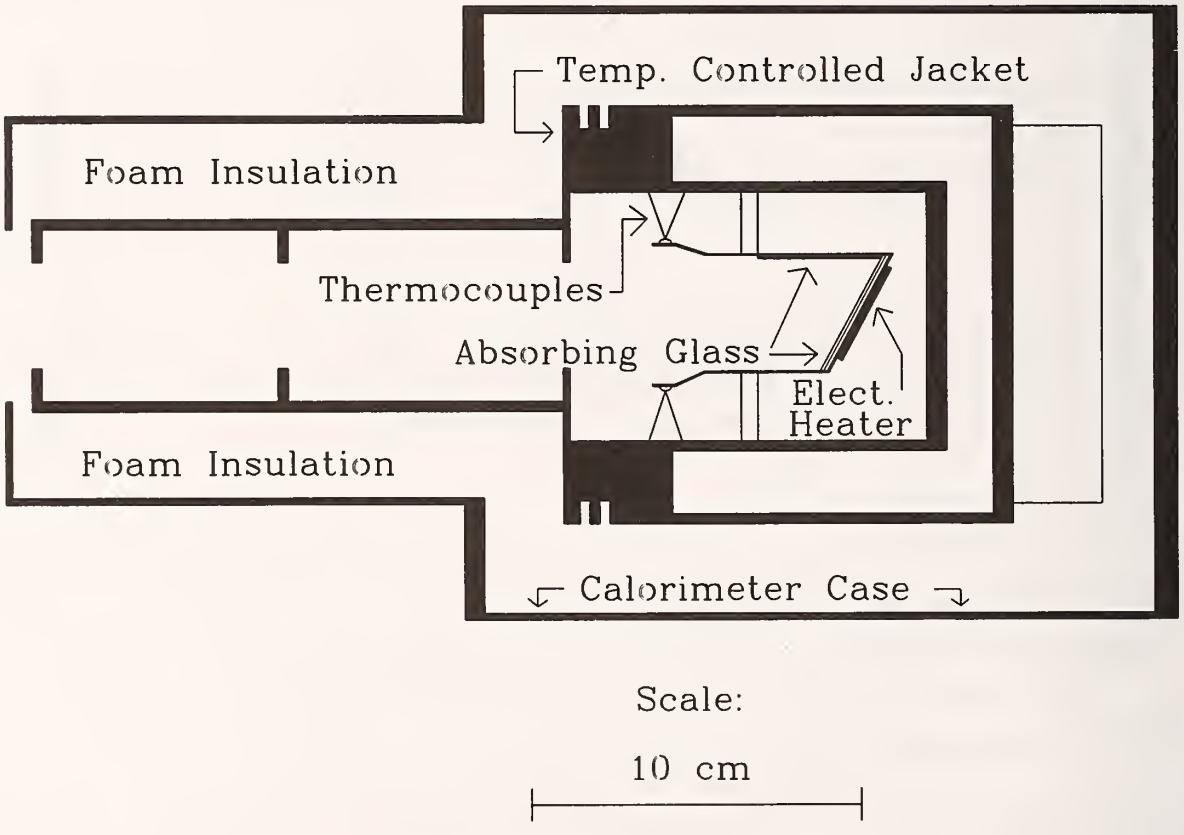

Figure 5. QUV calorimeter cross section.

4.1 Temperature Sensing Thermopile

A thermopile measures the difference in temperature between the absorbing cavity and the constant-temperature jacket. Change in thermoelectric voltage output represents a measure of the absorbed energy. An electrical heater wire in thermal contact with the cavity is attached near the location where the laser radiation is primarily absorbed. This provides the means to calibrate the response of the calorimeter in terms of electrical energy input. The calorimeters have been constructed to maximize the equivalence between electrical and laser energy inputs.

The cavity temperature is monitored by the thermopile, which consists of 20 hot junctions made of Type-E thermocouple wires bonded to the gold-plated cavity surface. Junctions are bonded using a thermally conducting epoxy which has excellent electrical insulating and chemical resistance properties. The 20 cold, or reference, junctions are bonded to the temperature-controlled jacket using the same epoxy. Each junction has a temperature sensitivity of about 50 μV/°C, so the total thermopile has an approximate sensitivity of 1 mV/°C.

The electrical calibration factor for each QUV calorimeter is about 15 J/mV. Therefore, an energy injection of 15 J will produce a maximum estimated temperature change in the cavity of approximately 1 °C. This temperature increase is small enough that the thermal coefficients (heat capacity and thermal conductivity) remain relatively constant during the measurement process. Also, both the radiative and convective heat transfers are nearly linear for this small temperature gradient.

4.2 Absorbing Cavity Structure

Since the calorimeters are intended to measure the energy from excimer laser sources, they must be able to absorb the pulsed radiation without incurring thermal or photochemical damage. The induced temperature increase for a given energy deposition is directly related to the volume of material through which the energy is dispersed. Therefore, the larger the volume over which a given amount of energy is absorbed, the smaller the corresponding temperature change. Black paint or other black materials (known as surface absorbers) absorb the radiation within a small volume of material. The resulting temperature changes can be large for this type of absorber. Pulsed laser radiation is deposited much more rapidly than the energy can diffuse away from the absorption region, and ablation of the absorber may result.

These characteristics severely limit the use of surface absorbing materials with pulsed laser sources. Instead, volume absorbing materials, such as colored glass filters, are used. As the laser radiation propagates through these types of materials the power (or energy) density decreases exponentially in the form

$$I(x) = I_0 e^{-\beta x}, \quad (1)$$

where I_0 is the incident energy intensity, I(x) is the intensity within the material at a distance x normal to the glass surface, and ß is the absorption coefficient for the material. For materials with large ß, energy is absorbed more rapidly with distance, and the resulting temperature increase at the surface (where the absorbed intensity is maximum) of the material is larger. In materials with small

ß, the energy is absorbed more slowly (with respect to x) and is thus spread through a larger volume. Since the thickness of the absorbing material must be large enough that essentially all the energy gets absorbed, smaller ß materials require greater thicknesses. Heat transfer becomes a consideration because in a thicker piece of glass the heat will take longer to conduct to the copper cavity. Thus, a compromise between heat transfer and thermal damage must be made when selecting the appropriate material and thickness.

The absorber material selected for the initial QUV calorimeters was ionically colored glass [9]. The manufacturer's transmittance data of the colored glass were compared to values measured at NIST. In the 248 nm wavelength region, the transmittances from both sources of data are in close agreement. Based on this information, the absorption coefficient calculated for the colored glass is 3.32/mm. Less than 0.1 percent of the incident energy will be transmitted through the 2 mm thick glass plate.

The filter is thin enough (2 mm) that the laser-generated heat can be conducted into the copper cavity relatively quickly. As shown in Figure 6, two pieces of colored filter glass are bonded with thermally conducting epoxy to the back of the cavity structure. The piece at the back of the cavity (angled at 60°) is 2 mm thick, and the piece at the top is 1 mm thick. The incident laser beam strikes the 2 mm thick glass where most of the radiation travels through the glass and is absorbed. The radiation reflected from the front surface of the 2 mm glass then strikes the 1 mm thick glass (at 30° angle of incidence) where most of the remaining radiation is absorbed. The small amount reflected from the front surface of the 1 mm glass strikes the absorbing black paint on the inside of the cavity.

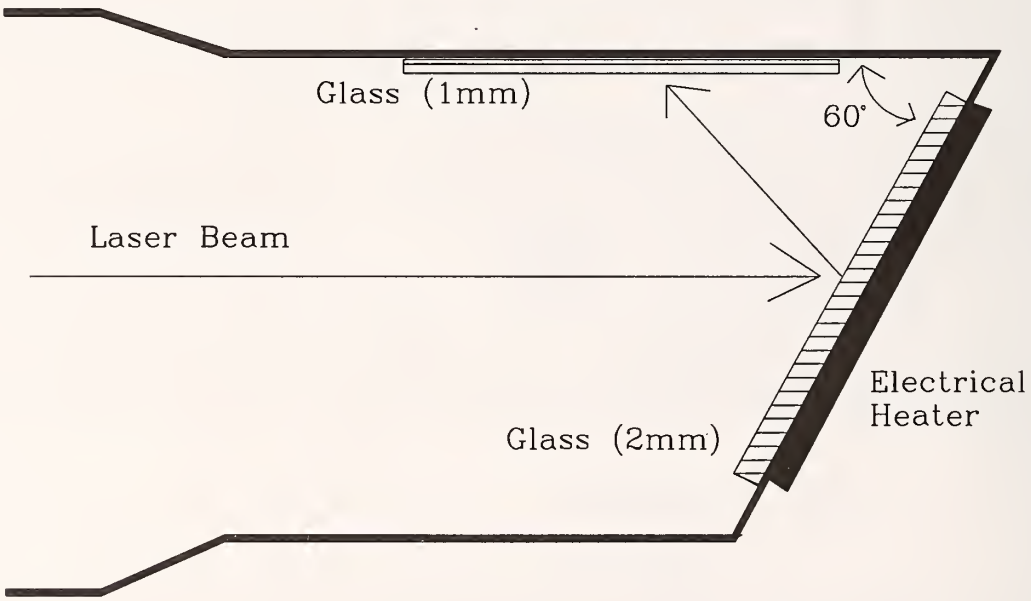

Figure 6. QUV cavity cross section.

To calculate the energy reflected from the surfaces of the glass absorbers, the refractive index of the glass for the 248 nm excimer wavelength must be determined. This was done by performing a curve fit to a Sellmeier equation using three data points provided by the glass manufacturer [10]. The resulting curve fit furnishes an index of refraction for UG 11 (at 248.4 nm) of ~1.62. Fresnel's laws of reflection were applied for dielectric materials at 30° angle of incidence, and yielded the front surface reflectances shown in Table 4.1.

The case where the least energy is absorbed by the initial filter is for radiation linearly polarized in a plane perpendicular to the plane of incidence. In this case 7.9 percent of the incoming laser beam energy will be reflected from the surface of the 2 mm glass and 7.9 percent of the remaining beam will be reflected from the 1 mm glass. Accordingly, about 0.8 percent of the incident beam energy strikes the black paint. However, for the QUV system the excimer laser is unpolarized; thus about 0.34 percent reaches the black paint, where it undergoes 95 percent absorption as specified by the coating manufacturer. We estimate less than 0.02 percent of the original beam energy is not absorbed by the cavity at this point. If the flat black paint has partial specular reflection, the light again encounters absorption at another cavity wall. The geometry of the cavity allows a negligible amount of incident radiation to scatter out. This same geometry was used on the Q-series calorimeters, and measurements on that device confirmed this conclusion [2].

Table 4.1. Front surface reflectance for colored glass filter at 248 nm (30° incidence).

Polarization	Reflectance
Unpolarized	0.058 ± 0.004
Perpendicular	0.079 ± 0.012
Parallel	0.037 ± 0.004

4.2.1 Absorber Material

Schott Glass UG11 filter glass was employed as the volume absorber [9]. A piece 2 mm thick was used as the main absorber, and a 1 mm section as the secondary absorber. This glass has been damage-tested with high intensity 248.4 nm laser pulses having a FWHM of about 30 to 35 ns. The excimer beam was focused to increase the energy fluence above typical operating conditions. The maximum energy fluence on the UG11 filter was approximately 200 mJ/cm^2 per pulse. No surface damage was visually observed for pulse repetition rates of 1 and 10 Hz for 1 to 2 minute durations.

4.3 Calorimeter Output Analysis

The theory of isoperibol calorimeters [3] predicts that the temperature (voltage) output can be expressed as an infinite series of exponential terms. The voltage output of the thermopile is used as the output variable and is assumed to be linearly related to temperature. At some time after energy injection, the higher order terms become negligible, and the output can be described by a single exponential equation,

$$[V(t)-V_\infty] = (V_0-V_\infty)e^{-\alpha t}, \quad (2)$$

V_∞ = voltage at an infinite time after energy input,
V_0 = voltage at time t_0, any time where the output is described by a single exponential, and
α = cooling constant.

The output voltage of the thermopile in the calorimeter is sampled and stored with a computer controlled data acquisition system. The resulting voltage-time information must then be processed to determine the energy received by the calorimeter. Figure 7 shows a typical voltage output of a QUV isoperibol calorimeter during a measurement.

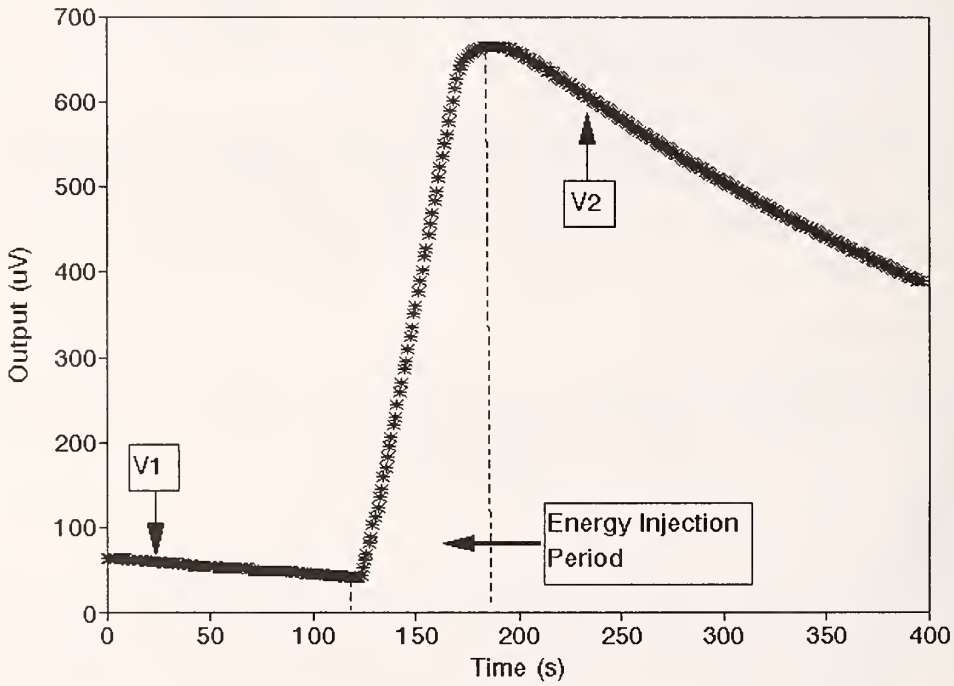

Figure 7. Calorimeter output voltage as a function of time.

Energy (either electrical or laser) is deposited during the interval labeled "Energy Injection Period." Voltages V_1 and V_2 at times t_1 and t_2 occur long enough after an energy injection that the output is described accurately by a single exponential decay factor.

Laser input can be a single pulse or a series of pulses which occur during the energy injection period. Heat flow in the glass absorber and the thermal time constant of the cavity act to thermally integrate the laser pulses. This allows the absorption of laser pulses to produce a response equivalent to a continuous injection of electrical energy.

According to the first law of thermodynamics (as applied to this calorimeter), the energy absorbed by the calorimeter is equal to the change in internal energy plus the heat transferred from the system during a measurement. The change in internal energy is proportional to the quantity $(V_2 - V_1)$, and the heat transfer value is proportional to the quantity

$$\alpha \int_{t_1}^{t_2} [V(t) - V_\infty] dt. \tag{3}$$

Theory [11] predicts that the output of such a device is related to the total energy absorbed by the calorimeter by

$$E = K[(V_2 - V_1) + \alpha \int_{t_1}^{t_2} [V(t) - V_\infty] dt], \tag{4}$$

where E is the energy absorbed and K is a proportionality constant. The proportionality constant (calibration factor) is actually a combination of a weighted heat-capacity and heat-transfer function of the structure of the calorimeter cavity. The value of K is determined electrically by injecting known energy and then using the voltage curve to solve eq (4). Unknown parameters α, V_∞, V_1, and V_2 are found for each measurement run by performing a least-squares fit (using eq 2) to the voltage data of the calorimeter in the regions near V_1 and V_2.

4.4 Electrical Calibration of the QUV Calorimeters

The QUV reference standard calorimeters are electrically calibrated by dc substitution, which provides traceability to electrical standards. The schematic in Figure 8 shows the basic configuration for electrical calibration runs. During an electrical calibration run, the computer commands the programmable power supply to turn on a predetermined voltage to the standard resistor and calorimeter resistance heater. This voltage is read by the digital voltmeter. A known electrical energy is dissipated by the heater, and the resulting cavity temperature change is monitored with the thermopile signal output as measured by a nanovoltmeter. The voltage data are logged and processed by the computer using algorithms based on calorimeter theory, as outlined in Section 4.3.

Electrical calibration runs are performed under control of the computer. Parameters are chosen by the operator to control the energy and the injection time. Automatic repetition of runs is possible with software control of the program Excimer Laser Calorimeter 3.0, allowing large amounts of data to be taken without operator intervention. All equipment is turned on and allowed to warm-up for one hour and reach operating equilibrium before any calibration runs are realized.

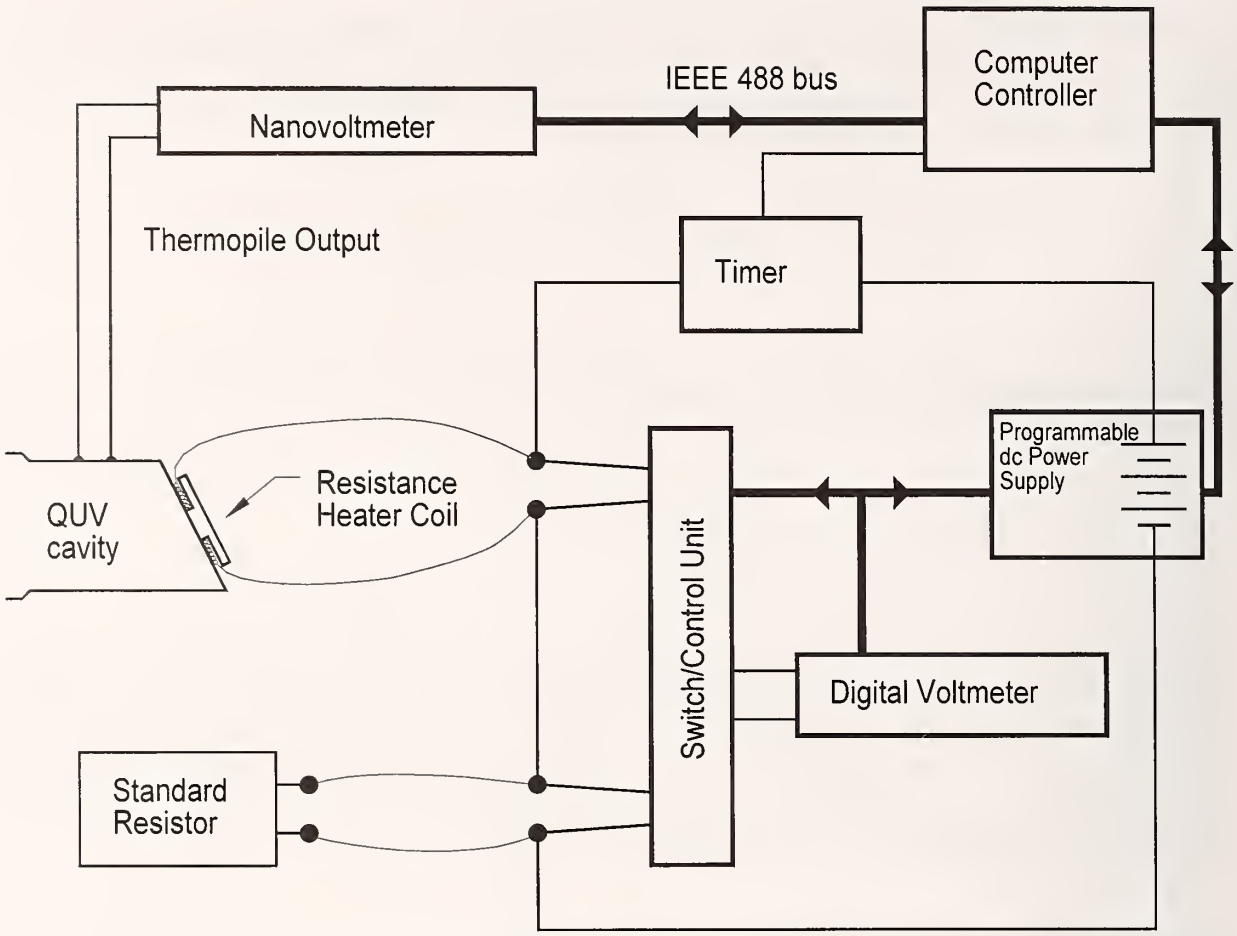

Figure 8. Electrical calibration configuration.

5. CALIBRATION OF LASER ENERGY OR POWER METERS

A typical set-up for calibrating laser energy or power meters is shown in Figure 1. The IUT is positioned in the beam which produces the required test conditions. The QUV standard is located in a beam which provides enough total energy for the calorimeter to operate within its measurement range. All instruments are optically aligned and then allowed to thermally stabilize in the system enclosure before calibration measurements are performed. Electronic instruments are powered on and allowed one hour warm-up to reach operating temperature.

5.1 Performance Capabilities of the 248 nm Calibration System

This calibration system is designed to measure pulsed laser energy and average power at the excimer wavelength of approximately 248 nm. Although the standard reference calorimeters measure total energy injected, the calibration system can be used to measure other laser-beam characteristics such as average pulse energy or average power. In fact, these two measurement quantities are most often requested by laser power or energy meter calibration customers.

The calibration system has the following capabilities in the main transmitted (m = 0) beam.

Laser Wavelength: 248.4 ± 0.7 nm
Laser Spectral Width: 0.3 nm
Beam Diameter (adjustable): Maximum = ~20 mm, Minimum = ~5 mm
Pulse Energy @ full open aperture: 100–150 mJ
Maximum Average Power @ full aperture: ~7.5 W
Pulse Repetition Rate (PRR): 0.5–50 s^{-1}
Pulse Width: ~30–35 ns
QUV Calorimeter Total Energy Measurement Range: 0.6–15 J
Fused-Silica Beamsplitter Ratios (approximate): 25, 620

The energy and power calibration ranges of the system are extended by using a wedged beamsplitter with the QUV calorimeters. Attenuation is available to reduce the beam energy and allow calibration of energy meters down to 1 mJ total energy. The system cannot achieve all powers or energies at all beam aperture diameters. Laser power/energy meters to be calibrated should be able to operate within the ranges listed above. Specific calibration requirements must be discussed with NIST staff to determine whether the system can be configured to meet customer requirements.

5.2 Calibration of Energy Measuring Instruments

Before average pulse energy calibrations are made, the excimer laser is filled with KrF gas and checked for stable pulse operation. Discharge control voltage is checked to see if it can maintain a stable laser pulse output during one measurement run. Laser pulse energy can be monitored for fluctuations with a sensor internal to the laser or with an external pyroelectric detector aligned in a low-energy beam. Laser output, to be considered stable (for this laser), has a pulse energy standard deviation on the order of 0.7 to 1.5 percent. Laser pulse energy which drops or cannot be maintained during a measurement run is an indication to the operator that the laser needs to be recharged with gas. For a meter which measures total energy the laser pulse stability is not critical since the beamsplitter allows both the IUT and the QUV calorimeter to simultaneously measure total energy.

Each measurement run of the system is controlled by the operator and the data-acquisition system. Once the measurement run is started with the parameters set by the operator, the excimer laser operation is started manually, and pulse amplitude is allowed to stabilize with the injection shutter closed. Manual start/stop of the laser is required for safety reasons.

Data-acquisition instruments log the QUV thermopile voltage throughout the measurement run for later processing. Two seconds before the shutter opens, the computer ramps the laser pulse rate up to that required for the calibration. The shutter opens, allowing injection of laser energy. The IUT logs the pulse energy with its own electronics or the operator manually records the display value, depending on the configuration. After the shutter closes, the QUV voltages continue to be recorded until the data processing is completed under software control. The computer displays the total energy measured by the QUV calorimeter, and this value is used along with the calibrated beamsplitter value and IUT data to calculate a calibration factor. Enough runs are performed to achieve a good statistical sample and are processed according to NIST measurement and uncertainty guidelines covered in Section 6.

5.3 Calibration of Power Reading Meters

Meters that measure average power are calibrated similarly to energy meters. Again, stable laser operation is important and checked with the internal laser-pulse monitor or an external pyroelectric detector. Stable laser operation is achieved through the power lock feature of the excimer laser, which automatically adjusts the control voltage to compensate for pulse energy fluctuations. At higher pulse repetition rates this feature does not always function properly. Then the control voltage can be locked to preset value by the operator, and the pulse energy is monitored with the internal laser sensor to see whether it remains constant over the measurement run.

Additional precautions are taken to ensure valid calibration results when measuring average power of a pulsed laser. Laser power meters usually have thermal sensing heads. These heads typically have response times on the order of seconds to tens of seconds. To ensure that laser pulses are averaged, the laser should be run at a *minimum* of 10 Hz unless otherwise instructed by the customer.

The laser injection period, beamsplitter ratio, and total energy measured by the QUV calorimeter are used to calculate the average power incident on the IUT. The calibration factor is calculated from the power meter data. Enough runs are performed to achieve a good statistical sample, and processed according to NIST measurement and uncertainty guidelines covered in Section 6.

For more complete details on the measurement procedures and routines please see Appendix B and the NIST Excimer Laser Calibrations - Technical Manual.

5.4 Laser Meters for Calibration

Meters suitable for calibrated measurement of excimer laser power or energy may be purchased from several of the manufacturers listed in laser-industry directories and buyers' guides. Typically the meters consist of a thermal or pyroelectric detector head coupled with signal processing and display electronics. Semiconductor sensors cannot now be calibrated with the QUV system because calibrated beamsplitter ratios that attenuate the laser pulse energy below the saturation energy of these very sensitive detectors are not available.

Stand-alone sensor heads can be calibrated as well, but then the customer's readout device is not included in the calibration measurement. This can lead to higher calibration uncertainties unless the customer's display device and connecting cables are independently characterized.

For each calibration, the associated measurement uncertainty is analyzed, taking into account the applicable conditions and data from the IUT. Total expanded uncertainties (as discussed in detail in Section 6.2) in the calibration of 248 nm laser power and energy meters typically range from 1.6 to 2 percent with the present system uncertainty assessment. A stand-alone thermal head measuring average power can be calibrated to a similar uncertainty if a high-accuracy voltmeter can be used for the readout and data recorded by the control computer. Average pulse energy calibrations of a pyroelectric head with an oscilloscope readout are often in the 2.5 to 3 percent uncertainty range due to the less accurate signal-measurement capabilities of typical waveform-recording devices.

6. MEASUREMENT UNCERTAINTY

The total uncertainty associated with a particular laser power or energy measurement is composed of the individual uncertainties of the components of the system. The actual magnitude of each component is unknown; otherwise the result could be correspondingly adjusted to eliminate the error.

Uncertainty estimates for our laser energy measurements are assessed using the following guidelines [12][13][14]. To establish the uncertainty limits, the sources of error are separated into Type A and Type B components. Components of uncertainty arising from a random effect which are evaluated by statistical methods are called Type A uncertainty. Components of uncertainty arising from a systematic effect which are evaluated by other means are called Type B uncertainty.

$$S_r = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N_r - 1}} , \quad (5)$$

Type A uncertainties are assumed to be independent. The standard deviation S_r for each component iswhere the x_i values represent the individual measurements, $\bar{x}$ is the mean of the measurements, and N_r is the number of x_i values used for a particular component of Type A uncertainty. The standard deviation of the mean is $S_r/N_r^{1/2}$, and the total standard deviation of the mean is $[\Sigma(S_r^2/N_r)]^{1/2}$, where the summation is carried out for all the Type A uncertainty components.

The Type B evaluation of standard uncertainty is derived from scientific judgement based on previous measurement data, manufacturer's specifications, and any other relevant knowledge. For the QUV calibration system, all Type B uncertainties are assumed to be independent and have rectangular or uniform distributions (that is, each has an uniform probability of being within the region $\pm\delta_i$ and zero probability of being outside that region). If the distribution is rectangular, the standard deviation σ_s of each uncertainty component is equal to $_i\delta/3^{1/2}$, and the total standard deviation is approximated by $(\Sigma\sigma_s^2)^{1/2}$, where the summation is performed over all Type B uncertainty components.

The expanded uncertainty is determined by combining the Type A standard deviation of the mean and the Type B standard deviation in quadrature and multiplying this result by a coverage factor of 2. The expanded uncertainty U is then

$$U = 2\sqrt{\sum \sigma_s^2 + \sum \frac{S_r^2}{N_r}} . \quad (6)$$

The number of decimal places used in reporting the mean value of the measurements is determined by expressing the expanded uncertainty to two significant digits.

6.1 QUV Reference Standard Calorimeter Uncertainty

The Type A evaluated uncertainty components for the QUV calorimeters are:

(1) Electrical Calibration: The calorimeters are calibrated by performing a large number of electrical measurements to determine an average calibration factor. The imprecision is an estimate of the error due to the scatter of individual measurements about the mean value.

Typically, a set of 20 electrical calibration runs at a specific energy and injection time exhibits a standard deviation less than 0.1 percent. For calibration energies less than 1 J the standard deviation in the electrical-calibration factor is slightly higher, but usually less than 0.15 percent.

The electrical calibration uncertainty of the QUV calorimeters was evaluated over the entire operation range. Measured energies ranged from 0.6 to 25 J, and injection durations from 10 to 180 s. A selection of 70 electrical calibration runs with widely varying energies and injection times yielded an average electrical calibration factor with a standard deviation of 0.5 percent. Since it is not practical to maintain a comprehensive electrical-calibration history at every energy and injection period, the uncertainty has been set at 0.5 percent. This component is not a dominant factor and lowering it will not significantly decrease the expanded uncertainty until other components can be reduced.

The Type B evaluated uncertainty components of these QUV calorimeters are:

(1) Inequivalence: This is the error due to the inequivalence between electrical and laser energy deposition. For a given absorbed energy, the output of the calorimeter may be different for different distributions of heat. The QUV calorimeters are designed to force the heat to flow in a manner which minimizes this inequivalence. The QUV calorimeters are of the same design, geometry and physical dimensions as the previously evaluated Q-series calorimeters. The Q-series inequivalence was derived from measurement intercomparisons with the C-series national standard calorimeters at a wavelength of 1.06 μm. The estimated inequivalence from the measurements is 0.48 percent.

Preliminary experimental comparisons were accomplished by calibrating the QUV calorimeters with the Q-series, pulsed 1.06 μm system. At 1.06 μm, the absorption of the UG11 glass is very close in value to that of the IR glass used by the Q-series calorimeters. Thus, the QUV calorimeters should function equally well at this IR wavelength. Results showed that calibration factors were very close when data from the 1.06 μm laser calibration system when compared to the electrical calibration factors obtained with the QUV system. The calibration factor difference was 0.43 percent for QUV-1, and 0.52 percent for QUV-2, providing further confirmation of the inequivalence estimate and calorimeter consistency.

(2) Absorptivity: This error is due to laser radiation which is reflected (or scattered) back out of the cavity. Escaping radiation does not contribute to heating the cavity and, consequently, causes an error in the measurement since it is assumed that all the incident electromagnetic energy is converted to heat in the cavity. The cavity geometry and absorbent coatings minimize this error.

Backscatter measurements on the Q-series cavity were made at 1.06 μm and the amount scattered was below detection. A conservative upper limit on this uncertainty was set at 0.1 percent for the Q-series. The QUV cavity is the same geometry. By calculation, the energy not absorbed in the multiple reflections in the cavity is less than 0.02 percent at 248.4 nm as shown in Section 4.2. If the black paint is more nearly specular or less absorbing than specified, the cavity geometry still forces absorption of all but a small fraction of the laser energy. Also, some of the UV photons which strike the black paint in the absorber cavity may remove the paint instead of convert to thermal energy, but this has not been observed. An excimer laser was not available to directly test the QUV cavities for scattering losses at the time of construction. A conservative upper limit on this uncertainty was set to 0.2 percent.

(3) Heater Leads: During the electrical calibrations some heat is generated in the copper wire leads which connect to the heater coil. This heat is not deposited on the cavity and causes an error in the calculation of the energy going to the heater. Lead resistance was measured as percentage of the total resistance heater and is ≤ 0.35 percent. A four-wire measurement technique was used to determine this value.

(4) Electronics: This component is due to the uncertainties in the electronic equipment used. These instruments include digital voltmeters and timing systems. The uncertainties in the electronic instruments are typically much smaller than the other uncertainty components. Manufacturers' stated accuracies and electrical tests were used to estimate an upper limit of 0.1 percent.

(5) Injection Timing: This component arises from uncertainty in the injection time interval of electrical or laser energy to the calorimeter during a calibration run and will affect average power calibrations. Finite switching times from the dc power supply result in an injection time uncertainty of less than 0.05 percent for 50 s, which is the shortest injection time used for average laser power calibrations. Longer injection times result in less uncertainty, and a conservative upper limit of uncertainty was set to 0.1 percent.

The estimated combined uncertainty of the energies measured by the QUV calorimeters is summarized in Table 6.1. The uncertainty due to inequivalence value is based primarily on the uncertainty assessment for Q-series calorimeters, which is expected to apply to these calorimeters because of their inherent similarity.

Table 6.1. QUV calorimeter expanded uncertainty

Source	Standard deviation (%)
Inequivalence (Type B)	0.48
Absorptivity (Type B)	0.20
Heater leads (Type B)	0.35
Electronics (Type B)	0.10
Injection timing (Type B)	0.10
Electrical calibrations (Type A)	0.50
Expanded uncertainty	± 0.75

6.2 Calibration System Measurement Uncertainty

The total uncertainty of a laser meter calibration must not only include the QUV uncertainties but also contributions from the beamsplitter, laser instability, and other potential error sources, including data from the IUT. The following sources of uncertainty were evaluated to complete the total measurement uncertainty.

(1) Laser stability: Laser stability directly impacts calibration measurements of average power and average pulse energy. The QUV calorimeters measure *total* energy, and average power or pulse energy can be calculated from the total energy, the energy injection time, and the pulse rate. Thus some uncertainty will result from the pulse-to-pulse instability of the laser.

Pulse-to-pulse energy stability was evaluated with the internal excimer laser pulse monitor and data from a pyroelectric laser-energy meter. Instability of the pulse energy was about 1 to 1.5 percent, but the net effect on calibration factors was less than this due to averaging. Laser energy measurements have shown standard deviations of 0.3 to 1 percent for a variety of meter types.

Average-power calibrations were also investigated, comparing results with stable laser operation to measurements performed with laser-pulse instability as high as ±5 percent. The resulting effect on average power calibrations showed less than 0.4 percent difference between unstable and stable laser runs. Although laser pulse-to-pulse instability will be partially accounted for in the determination of overall standard deviation, additional uncertainty is evaluated as a Type B component, with an upper limit of 0.75 percent for stable laser operation.

(2) Beamsplitter ratio: A beamsplitter ratio is used in all calibration measurements for the calculation of the laser energy incident on the IUT. The theoretical values of these ratios are summarized in Table 3.1. There is a 3 to 5 percent difference between the theoretical beamsplitter ratios and those measured with the QUV calorimeters (Table 3.2). As mentioned earlier, UV damage to the fused-silica wedge is expected to modify its transmission and reflection properties. Thus, the measured ratios are considered to be more accurate, and the calculated ratios are used only for guidance in the overall evaluation of beamsplitter ratios.

The beamsplitter uncertainty source has been evaluated with both Type A and B procedures. Measurements of the beamsplitter ratios 0/+1 and +1/+2 have typical standard deviations of 0.3 to 0.6 percent for 30 measurement runs. The most recent ratio measurement data is used to determine the beamsplitter values and associated Type A uncertainty estimates. The Type B uncertainty is included because using a laser to determine the ratio further exposes the beamsplitter to intense UV radiation, possibly changing the properties as the measurement is being made. As we evaluate laser beamsplitter ratios from the last three years, we expect to lower this uncertainty estimate. This evaluation will also give an indication of how often beamsplitter measurements must be made to maintain a lower Type B uncertainty estimate.

(3) Measurement data from the Instrument Under Test (IUT): Calibration measurements on the IUT provide data which can be evaluated with statistical methods, giving Type A uncertainty components. Results will lead to a mean and standard deviation used in the calculation of the overall uncertainty of the measurements.

(4) Beam pathlength: Absorption or scattering of UV light by the constituents in air will cause the relative pulse energy arriving at the QUV standard or the IUT to be dependent on pathlength. Measurements made to quantify this effect show a small impact (<0.04 percent, or less than one standard deviation) when the beam pathlength is changed by ≤40 cm. Calibrations are usually performed under conditions where beam pathlengths differ by no more than ±2 cm (from those used for beamsplitter calibrations) to reduce this effect. Occasionally, the required pulse-energies dictate a physical configuration where the pathlengths differ by as much as 25 cm. This uncertainty is evaluated as a Type B component, with a magnitude of 0.02 percent.

The overall measurement uncertainties for the QUV calibration system operating at 248.4 nm are summarized in Table 6.2. Typical expanded uncertainty values for laser power or energy meters are in the range of 1.6 to 2 percent.

Table 6.2. Typical QUV measurement system uncertainties.

Type A			Type B	
SOURCE	S_r (%)	N	SOURCE	δ_i (%)
Electrical calibration	0.50	70	Inequivalence	0.48
Beamsplitter cal. (0/+1)	0.30	30	Absorptivity	0.20
Beamsplitter cal. (+1/+2)	0.60	30	Heater leads	0.35
IUT cal. (typical)	0.2–1	10	Electronics	0.10
			Injection timing	0.10
			Beamsplitter	1.00
			Laser instability	0.75
			Beam pathlength	0.02

7. MEASUREMENT ASSURANCE

Confidence for high-quality performance and precision of the QUV system is achieved with electrical calibrations, frequent measurement of laser beamsplitter ratios, calibration of two different check standards, and periodic evaluation of sources of uncertainty.

7.1 Electrical Calibration History

Electrical calibrations are performed periodically to provide a history at injection times and energies necessary for specific laser meter measurements. Additional electrical runs are also acquired at the energies (0.6 and 15 J) used for laser beamsplitter ratio measurements. This provides a statistical history for tracking the stability of the QUV calorimeters. As shown in Table 7.1 the difference in electrical calibration factors is less than 0.2 percent in the last three years.

Table 7.1. Electrical calibration factors (J/mV).

Old electrical cal factors (1994)	New electrical cal factors (1997)	% difference
QUV-1 (low energy) 15.20 ± 0.13	QUV-1 (low energy) 15.18 ± 0.13	0.13
QUV-1 (high energy) 15.23 ± 0.13	QUV-1 (high energy) 15.21 ± 0.13	0.07
QUV-2 (low energy) 15.87 ± 0.13	QUV-2 (low energy) 15.86 ± 0.13	0.06
QUV-2 (high energy) 15.85 ± 0.13	QUV-2 (high energy) 15.83 ± 0.13	0.13

7.2 Laser Beamsplitter Ratio Measurements

As discussed in Section 3.3, frequent ratio measurements are necessary because of potential UV-induced damage in the fused-silica beamsplitter. A small set (5 to 10 measurements) is taken before or after each laser meter calibration to confirm that the specific ratio used has not significantly shifted.

The comprehensive measurements outlined in Section 3.3, in which the calorimeters and nanovoltmeters are physically interchanged to cancel offset errors, are administered periodically to obtain the beamsplitter ratios. The measurements are time consuming, and there is risk of damage to the calorimeters from the physical movement, so the frequency with which these measurements are executed is limited. Sets of ratio measurements are performed at least once a year. Based on accumulated data, it is recommended that ratios be measured twice yearly in order to lower uncertainty estimates for the beamsplitter ratios and to track ratios more completely. Uncertainty assessment for these measurements is covered in detail in Section 6.

7.3 Check Standard Calibrations to Monitor the QUV System

Two check standards have been maintained in an attempt to evaluate and monitor calibration precision using technologies independent and external to the QUV system. The check standards, one

to assess laser power and the other to measure pulse energy, were purchased from independent U.S. companies.

The laser power meter (Check Standard #1) functions at excimer laser wavelengths with a very durable UV absorber coating that can withstand 30 W of average power and pulses of 15 J/cm^2. Calibration factors for this meter have been very consistent since the inception of the QUV system, as shown in Table 7.2.

Table 7.2. UV laser power, check standard (#1) calibration.

Date	Cal factor (W/reading)	Laser PRR (pulses/s)	Average power (W)	Expanded uncertainty (%)
9/94	0.9375	10	unavailable	1.8
2/1/95	0.944	50–100	5–10	1.9
11/29/95	0.938	10	1.2	1.7
”	0.927	5	0.6	1.7
”	0.945	20	2.4	1.6
”	0.940	50	2.8	1.6
12/18/96	0.943	10	0.8–1.4	1.7
9/23/97	0.937	20	1.5	1.7

A pyroelectric, pulse-energy measuring detector (Check Standard #2) has been calibrated to provide long-term data on calibrations of this nature. Presently, only an oscilloscope readout device has been used during measurements, so the overall uncertainty of this type of calibration is greater than desired for this purpose. More-precise readout devices are being evaluated for possible application to improving the laser-pulse energy-calibration check standard. Calibration factors have been consistent and within the uncertainty levels estimated during the short period over which measurements have been recorded for this detector.

Table 7.3. UV laser pulse energy, check standard (#2) calibration.

Date	Cal factor (V/mJ)	Laser PRR (pulses/s)	Average pulse energy (mJ)	Expanded uncertainty (%)
10/26/95	1.20	5	1	2.8
”	1.18	5	0.04	2.8
1/27/97	1.17	5–15	0.3	2.8

7.4 Revising the Uncertainty Sources from Accumulated Data

A substantial volume of data has been accumulated from electrical calibrations, laser beamsplitter ratio measurements, and device calibrations. Estimates of system uncertainty for the beamsplitter ratio, injection timing, laser instability, and the IUT are essentially under evaluation every time a meter is calibrated and adjusted accordingly. Calibration-system uncertainty components will be evaluated annually with the past year's data and updated.

8. FUTURE CALIBRATION SYSTEM CHANGES

Inevitably, changes will be made to the QUV calorimeter-based 248 nm measurement system. The software will likely be converted from the current computer to a PC-based platform. Refinements in the instrument control may take place, but will probably be minor.

Investigation and testing of UV-grade optical materials other than fused silica may allow beamsplitters with smaller ratios to be used. Improvements in fused silica will likely provide more damage-resistant beamsplitters which will be stable in their attenuation factors and allow lowered uncertainties. A broadband-UV volume absorber is being investigated which may allow new calorimeters to be built which work at the excimer wavelengths of 157 through 351 nm.

The majority of modifications in the near future will probably be minor. Changes will be updated in the active documentation files for the system. While the details may no longer be completely accurate, this report should still adequately describe the service.

Major changes such as a new calorimeter design or measurement system will require the preparation of a new document.

ACKNOWLEDGMENTS

The development of the QUV calorimeters is based on the work of E. D. West and Douglas Franzen, who designed the original Q-series instruments. Credit also goes to Thomas R. Scott for project support and suggestions on data analysis. I am indebted to David J. Livigni and Robert Folsom for assistance in the final construction of the calorimeters and calibration system. Thanks also to Jeff Parker of Metric Systems for system software development. This work was supported by SEMATECH, a consortium of U.S. semiconductor companies.

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[10] Sellmeier equation, $n^2 = 1 + A\lambda^2/(\lambda^2 - B)$ where n is the refractive index at wavelength λ, and A and B are constants. The data points for a curve fit were obtained from Schott Glass Technologies Inc., Duryea, PA.

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APPENDIX A. Sample Calibration Report

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
ELECTRONICS & ELECTRICAL ENGINEERING LABORATORY
Boulder, Colorado 80303

REPORT OF CALIBRATION

LASER POWER and ENERGY METER
Manufacturer's Name
Meter Model ABC, Serial No. 123
Head Model XYZ, Serial No. 456

Submitted by:
Customer's, Name
Customer's Address

Calibration Summary

The laser power and energy meter was compared to the NIST standard calorimeters at a wavelength of 248 nm using a KrF excimer laser source. The laser beam incident on the detector had a circular cross section with an approximate diameter of 1.5 cm, and the test instrument was positioned so that the beam was centered on the absorbing surface. The power (or energy) impinging upon the test instrument was measured using a calibrated beamsplitter and a standard calorimeter (see Figure 1). For each energy measurement, 80 pulses were deposited within a 1 second time interval and a total energy reading was recorded. For each measurement of power, the radiation was deposited over a period of 180 seconds at a pulse rate of 40 Hz, and the steady state power reading was recorded. The ambient temperature during these measurements was approximately 23 °C and, before the measurements began, the test instrument was allowed to reach equilibrium with the laboratory environment. The actual power (or energy) striking the test instrument was calculated by multiplying the average power (or energy) measured with the reference standard by the beamsplitter ratio. The calibration factor was then found by dividing the test instrument reading by the calculated incident power (or energy).

Table I. Calibration Results (typical example)

Meter Range Setting	Nominal Power (Energy) Input	No. of Measure-ments	Meter Calibration Factor	Standard Deviation	Expanded Uncertainty
1 W	100 mW	10	1.01 Reading/W	0.67%	± 1.68%
1 J	250 mJ	10	1.04 Reading/J	0.89%	± 1.69%

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LASER POWER METER
Customer's Name
Meter Model ABC, Serial No. 123
Head Model XYZ, Serial No. 456

A summary of the measurements is given in Table I. If the readings of the test instrument are **divided** by the appropriate calibration factor listed in the table, then the resulting values will agree with those of the NIST laser measurement standards.

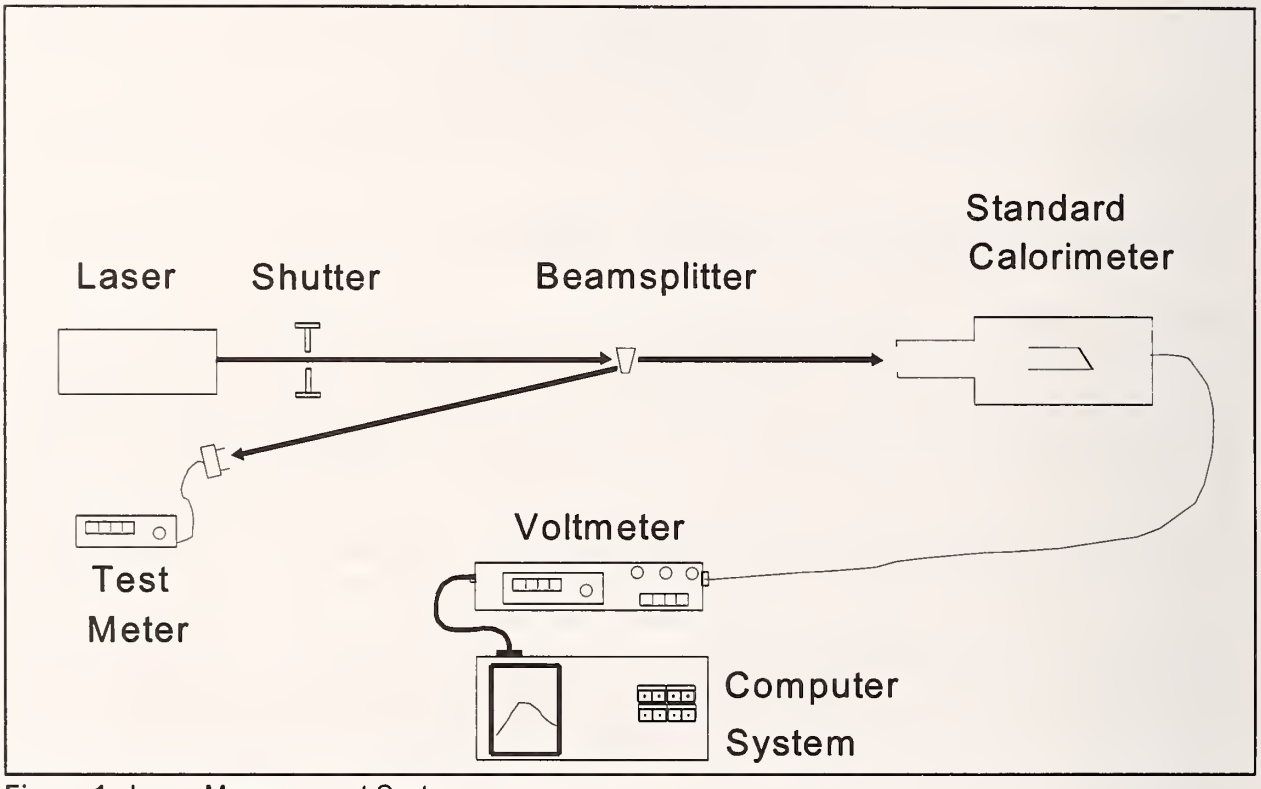

Figure 1. Laser Measurement System.

Uncertainty Assessment

The uncertainty estimates for the NIST laser energy measurements are assessed using the following guidelines. To establish the uncertainty limits, the error sources are separated into (1) Type A uncertainties, whose magnitudes are obtained statistically from a series of measurements, and (2) Type B uncertainties, whose magnitudes are determined by scientific judgement using all the relevant information available.

All the Type B uncertainty components are assumed to be independent and have rectangular or uniform distributions (that is, each has an equal probability of being within the region, $\pm\delta_i$, and zero probability of being outside that region). If the distribution is rectangular, the standard deviation, σ_s, for each Type B uncertainty component is equal to $\delta_i/3^{1/2}$ and the total standard deviation is approximated by $(\Sigma\sigma_s^2)^{1/2}$ where the summation is performed over all Type B uncertainty components.

The Type A uncertainties are assumed to be independent and normally distributed and consequently the standard deviation, S_r, for each component is

$$S_r = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N_r - 1}} , \qquad (1)$$

where the x_i values represent the individual measurements, $\bar{x}$ is the mean of the measurements, and N_r is the number of x_i values used for a particular Type A uncertainty component. The standard deviation of the mean is $S_r/N_r^{1/2}$, and the total standard deviation of the mean is $[\Sigma(S_r^2/N_r)]^{1/2}$, where the summation is carried out for all the Type A uncertainty components.

The total uncertainty is determined by combining the Type A and Type B standard deviations in quadrature and multiplying this result by a factor of 2. The expanded uncertainty, U, is then

$$U = 2\sqrt{\sum \sigma_s^2 + \sum \frac{S_r^2}{N_r}} . \qquad (2)$$

The values used to calculate the expanded uncertainty are listed in Table II.

The number of decimal places used in reporting the mean value of the calibration factors listed in Table I were determined by expressing the total expanded uncertainty to two significant digits.

LASER POWER METER
Customer's Name
Meter Model ABC, Serial No. 123
Head Model XYZ, Serial No. 456

Table II. NIST Pulsed-UV Measurement System Uncertainties

Type A			Type B	
SOURCE	S_r	N	SOURCE	δ_i
Electrical Calibration	0.50%	70	Inequivalence	0.48%
Beamsplitter Cal.	0.59%	30	Absorptivity	0.20%
			Heater Leads	0.35%
Test Meter Cal.	See	Table I	Electronics	0.10%
			Injection Timing	0.10%
			Beamsplitter	1.00%
			Laser Instability	0.75%
			Beam Pathlength	0.02%

For the Director,
National Institute of Standards
and Technology

Calibrated By:

Thomas R. Scott, Group Leader
Sources and Detectors Group
Optoelectronics Division

Rodney W. Leonhardt, Electronics Engineer
Sources and Detectors Group
Optoelectronics Division

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APPENDIX B. Calibration Procedure Outline

Instrument control and data analysis for the QUV calibration system are performed with custom software running on the system computer. (This system software will eventually be changed to a PC platform which is more currently supported.) Operational procedures for the software are documented in a manual titled "Upgrade to Q-series laser calorimeter data acquisition system" and kept on file in the calibration laboratory.

1. Ascertain the meter type and the desired calibration conditions from the customer.

2. From the system performance specifications (outlined in Section 5.1), calculate whether the requirements can be met.

3. Check the system output for those requirements, utilizing the calibrated lab transfer standard, check standard #1.

4. If the power/energy levels and beam diameter can be adjusted to match customer requirements, then the calibration can commence. At this point the customer should make arrangements for payment and shipping with the Office of Measurement Services, NIST-Boulder, (303) 497-3753.

5. Once the test meter arrives, unpack and set up the equipment to be calibrated in the QUV enclosure. The customer should include all cables and connectors necessary to calibrate the equipment. If NIST provides cables, then the customer should be notified that these differing conditions may change the calibration factor. Allow the detector head and electronics to stabilize at room temperature overnight.

6. Turn on the QUV calibration system electronics; then the test meter should be activated and allowed to warm up for at least one hour before calibration-quality measurements are made.

7. If necessary, perform electrical calibrations on a QUV calorimeter at an injection duration and energy level to match the desired measurement conditions.

8. Turn on the excimer laser, recirculating cooling water pump, and the external cooling water supply. When the laser is functional, use the laboratory transfer standard to set pulse energy levels necessary for calibrations. Adjust the beam diameter and collimation to allow use with two calorimeters.

9. Measure laser beamsplitter ratios to confirm that the ratio has not changed.

10. Configure the QUV calibration system for the desired performance specifications, including pulse energy, and beam diameter. Perform at least 8 to 10 calibration runs on the meter under test.

11. Calculate calibration factors and measurement uncertainty using NIST statistical guidelines. Prepare calibration report and return equipment with the original signed copy of the report to the Office of Measurement Services for return shipment.

APPENDIX C. Shipping Instructions

Meters should be shipped in well-padded foam or otherwise mechanical-shock insulated cases, appropriate for reshipment back to the customer. *Operation instructions or instruction manuals should be included, as well as the customer chosen set-up parameters for instrument functions*. The customer should include all cables and connectors that are necessary to calibrate the equipment as specified.

The excimer laser source beam has a nonuniform intensity profile as well as a short (~35 ns) pulse width. These two properties combine to produce laser pulses of very high peak-power which can damage absorber surfaces. Information on the damage threshold ratings of the sensor head should be included with the information sent to NIST. Absorber material test slides are very helpful in evaluating whether the excimer laser levels will damage a particular sensor head. Every effort is made to stay well below (5x to 10x below) the rated damage threshold, but the best way to be certain is to expose the same absorber material under the test conditions.

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